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Aircraft Airframe Cost Estimating Relationships: Bombers and Transports

R. W. Hess, H. P. Romanoff

December 1987

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This Note is part of a series of Notes that derive a set of equations suitable for estimating the acquisition costs of various types of aircraft airframes in the absence of detailed design and manufacturing information. A single set of equations was selected as being the most representative and applicable to the widest range of estimating situations. For bombers and transports, no single acceptable estimating relationship could be identified. Estimates for these aircraft should be developed by analogy or by using the equation set developed for all mission types.

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Aircraft Airframe Cost Estimating Relationships: Bombers and Transports

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PREFACE

This Note describes an attempt to develop a set of equations suitable for estimating the acquisition costs of bomber/transport airframes in the absence of detailed design and manufacturing information. In broad form, this research represents an extension of the results published in J. P. Large et al., *Parametric Equations for Estimating Aircraft Airframe Costs*, The RAND Corporation, R-1693-1-PA&E, February 1976, and used in the RAND aircraft cost model, DAPCA: H. E. Boren, Jr., *A Computer Model for Estimating Development and Procurement Costs of Aircraft (DAPCA-III)*, The RAND Corporation, R-1854-PR, March 1976.

The present effort was undertaken in the context of a larger overall study whose objectives included: (a) an analysis of the utility of dividing the full estimating sample into subsamples representing major differences in aircraft type (attack, fighter, and bomber/transport); and (b) an examination of the explanatory power of variables describing program structure and airframe construction techniques. Additionally, for the fighter subsample only, the study investigated the possible benefits of incorporating an objective technology measure into the equations. A detailed description of the overall study including the research approach, evaluation criteria, and database may be found in R. W. Hess and H. P. Romanoff, *Aircraft Airframe Cost Estimating Relationships: Study Approach and Conclusions*, The RAND Corporation, R-3255-AF, December 1987.

To address the issue of sample homogeneity, each of the subsamples, as well as the full sample, had to be investigated in detail with the ultimate goal of developing a representative set of cost estimating relationships (CERs) for each. The purpose of this Note is, therefore, to document the analysis of the bomber/transport subsample. Study results concerning the full estimating sample as well as the other subsamples are available in a series of companion Notes:

Aircraft Airframe Cost Estimating Relationships: All Mission Types, N-2283/1-AF, December 1987.

Aircraft Airframe Cost Estimating Relationships: Fighters, N-2283/2-AF, December 1987.

Aircraft Airframe Cost Estimating Relationships: Attack Aircraft, N-2283/4-AF, December 1987.

This research was undertaken as part of the Project AIR FORCE study entitled "Cost Analysis Methods for Air Force Systems," which has since been superseded by "Air Force Resource and Financial Management Issues for the 1980s" in the Resource Management Program.

While this report was in preparation, Lieutenant Colonel H. P. Romanoff, USAF, was on duty in the System Sciences Department of The RAND Corporation. At present, he is with the Directorate of Advanced Programs in the Office of the Assistant Secretary of the Air Force for Acquisition.

SUMMARY

This Note documents an attempt to derive a set of equations suitable for estimating the acquisition costs of bomber/transport aircraft. The estimating sample consists of eight bomber/transport aircraft with first flight dates ranging from 1954 to 1968. The aircraft technical data were for the most part obtained from either original engineering documents such as manufacturer's performance substantiation reports or from official Air Force and Navy documents. The cost data were obtained from the airframe manufacturers either directly from their records or indirectly through standard Department of Defense reports such as the Contractor Cost Data Reporting System.

The key result of this effort is that we were unable to identify a single acceptable estimating relationship for any of the individual cost elements or for the total program cost element. This discouraging result is not too surprising, however, since the bomber/transport sample is very small and not especially homogeneous. Estimates for proposed bomber/transport aircraft should be developed on the basis of analogy (using the data provided in this Note) or by using the equation set developed for all mission types (N-2283/1-AF).

CONTENTS

FIGURES

TABLES

MNEMONICS

AUW	Airframe unit weight (lb)
AVAUW	Ratio of avionics weight to airframe unit weight
BLBOX	Number of black boxes
CA	Cumulative average
DS	Development support cost (thousands of 1977 dollars)
$ENGR_{100}$	Cumulative engineering hours for 100 aircraft (thousands)
EW	Empty weight (lb)
EXPDV	Contractor experience designator (1 = yes; 2 = no)
FT	Flight test cost (thousands of 1977 dollars)
$LABR_{100}$	Cumulative manufacturing labor hours for 100 aircraft (thousands)
$MATL_{100}$	Cumulative manufacturing material cost for 100 aircraft (thousands of 1977 dollars)
$PROG_{100}$	Cumulative total program cost for 100 aircraft (thousands of 1977 dollars)
Q	Quantity
QC_{100}	Cumulative quality control hours for 100 aircraft (thousands)
SP	Maximum speed (kn)
TESTAC	Number of flight test aircraft
$TOOL_{100}$	Cumulative tooling hours for 100 aircraft (thousands)
USELD	Useful load fraction
WGWET	Ratio of wing area to wetted area
WTAREA	Wetted area (sq ft)

EVALUATION CRITERIA NOTATION

Notation	Explanation
EQ SIG: F-TEST	Equation as a whole is not significant at 5 percent level (based on F-statistic)
EXP MAG: variable mnemonic	Question exists regarding magnitude of variable exponent (reasonableness)
EXP SIGN: variable mnemonic	Sign of variable exponent does not agree with a priori notions
F	F-statistic
IO: aircraft identification	Based on "Cook's Distance," aircraft is indicated to be influential observation
LDIFF: variable mnemonic	Limited differentiation in dummy variable; coefficient determined by single observation or portion of dummy variable range not included in a subsample
MCOL: r(variable) > .7, .8, or .9	Indicates degree of intercorrelation of specified variable with other equation variables (only provided when threshold of .7 is exceeded)
N	Number of observations
R^2	Coefficient of determination
RP: CUR: OVER/UNDER	Residual pattern indicates that the most recently developed aircraft in the sample are over- or underestimated
RP: DIST	Residual pattern indicates that the error is not normally distributed with zero mean and constant variance
SEE	Standard error of estimate
VAR SIG: variable mnemonic	Variable is not significant at the 5 percent level (t-statistic)[1]

[1]Variable significance is provided in parentheses beneath each variable.

I. INTRODUCTION

Parametric models for estimating aircraft airframe acquisition costs have been used extensively in advanced planning studies and contractor proposal validation. These models are designed to be used when little is known about an aircraft design or when a readily applied validity and consistency check of detailed cost estimates[1] is necessary. They require inputs that: (a) will provide results that are relatively accurate; (b) are logically related to cost; and (c) can easily be projected prior to actual design and development. The intent is to generate estimates that include the cost of program delays, engineering changes, data requirements, and phenomena of all kinds that occur in a normal aircraft program.

Since 1966, RAND has developed three parametric airframe cost models.[2] These models have been characterized by: (a) easily obtainable size and performance inputs (weight and speed); (b) the estimation of costs at the total airframe level; and (c) the utilization of heterogeneous aircraft samples. They have normally been updated when a sufficient number of additional aircraft data points has become available to suggest possible changes in the equations. Such is the case with the present effort: the A-10, F-15, F-16, F-18, F-101, and S-3 have been added to the full estimating sample.[3]

In addition to the expansion of the database, we also examined: (a) the utility of dividing the estimating sample into subsamples representing major differences in aircraft type (attack, fighter, bomber/transport); (b) the explanatory power of variables describing

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[1]Examples of this latter application include the Independent Cost Analysis (ICA), prepared as part of the Defense Systems Acquisition Review Council (DSARC) process, and government analyses of contractor cost proposals during source selections.

[2]See Refs. 1, 2, and 3.

[3]Additionally, the F-86, F-89, and F3D, which were dropped from the DAPCA-III estimating sample, were reintroduced.

program structure and airframe construction techniques; and (c) the possible benefits of incorporating an objective technology measure into the fighter sample equations. In order to address the issue of sample homogeneity, each of the subsamples, as well as the full sample, had to be investigated in detail with the ultimate goal of developing representative sets[4] of cost estimating relationships (CERs) for each. The purpose of this Note is, therefore, to document the analysis of the bomber/transport subsample.

Section II provides brief descriptions of the database and statistical analysis methods. Section III gives some general indication, based on initial observations, of what can be expected in subsequent sections. Sections IV through XI provide, by cost element, data plots and each of the estimating relationships that meets our initial screening criterion with respect to variable significance. Section XII summarizes the main findings of the study. The appendix contains correlation matrixes.

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[4]A set encompasses the following cost elements: engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control.

II. DATABASE AND ANALYTICAL APPROACH

A detailed description of the research approach, evaluation criteria, and database for this study may be found in R-3255-AF. However, in order that this Note may have a degree of self-sufficiency, a synopsis of the database and analytical approach is presented prior to the reporting of results.

ESTIMATING SAMPLE

The full bomber/transport estimating sample consists of the following eight "new design" aircraft:[1]

Model	First Flight Date[2]
B-52	1954
B-58	1957
B/RB-66	1954
C-5	1968
C-130	1955
C-133	1956
KC-135	1957
C-141	1963

---

[1]The classification of an aircraft as new or derivative is not an entirely objective procedure. For example, although the B/RB-66 evolved from the A-3, the B/RB-66 is classified as a new design in the database. "During the course of B/RB-66 development, more than 400 alterations were made, including a two-degree change in wing incidence, a reduction in the sweep angle of the inboard wing trailing edge to decrease thickness/chord ratio and minimize pitchup, and a completely new fuselage layout, and these changes, added to the specialized equipment demanded for the various B/RB-66 versions, resulted in a full-scale development project" (Ref. 4, p. 149).

[2]The first flight dates presented in this Note are intended to reflect the first flight date of the version of the aircraft that was most representative of the aircraft which was to become operational. Put another way, these dates are intended to reflect the first flight date of the developmental aircraft and not earlier experimental or prototype aircraft.

DEPENDENT VARIABLES

Costs have been dealt with at both the total program level[3] and at the major cost element level (engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control).[4] The relative importance of the various cost elements is shown in Table 1 for four alternative production quantities. Other things being equal, the accuracy of the estimating relationship for manufacturing labor is of greatest concern because of the relatively large share of program cost represented by that cost element.

Table 1

PERCENTAGE BREAKDOWN OF BOMBER/TRANSPORT
AIRFRAME PROGRAM COSTS
(8 aircraft average costs)

	Quantity			
Cost Element	25	50	100	200
Engineering	21	19	16	13
Tooling	23	20	17	14
Manufacturing labor	29	33	37	41
Manufacturing material	11	15	19	23
Development support	6	5	3	2
Flight test	7	5	4	3
Quality control	3	3	4	4
	100	100	100	100

[3]Total program costs are "normalized" values and not the actual reported dollar amounts. They are normalized in the sense that the dollar amounts for engineering, tooling, manufacturing labor, and quality control have been determined by applying fully burdened, industry-average labor rates to the hours reported for each category.

[4]Cost element definitions are provided in Appendix A of R-3255-AF.

Engineering, tooling, manufacturing labor, and quality control are estimated in terms of manhours rather than dollars for two reasons: (a) it avoids the need to make adjustments for annual price changes, and (b) it permits comparison of real differences in labor requirements.[5] Manufacturing material, development support, and flight test do not lend themselves to this approach and were therefore estimated in terms of dollars (in this case, constant 1977 dollars).

POTENTIAL EXPLANATORY VARIABLES

To be included among the characteristics that were considered for inclusion in the CERs, a variable had to fulfill the following requirements:

1. It had to be logically related to cost: that is, a rationale had to be constructed that would explain why cost should be influenced by the variable;
2. It had to be "readily available" in the early stages of aircraft conceptualization; and
3. It had to have an *available* historical record.

During the formulation stage of this study, twenty aircraft characteristics were identified as potential explanatory variables for the bomber/transport sample CERs. Values for these characteristics, which are grouped into four general categories--size, performance, construction, and program, are provided in Table 2. Based on this table, the following observations are made:

1. For any of the three size measures, the C-5 is approximately twice as large as the next largest aircraft in the sample.

[5]The major limitation of the manhour approach is that it does not account for differences in overhead rates. Consequently, differences in such things as capital/labor ratios cannot be addressed.

Table 2

BOMBER/TRANSPORT AIRCRAFT CHARACTERISTICS

Characteristic	B-52	B-58	B/RB-66	C-5	C-130	C-133	KC-135	C-141	Mean	Standard Deviation
	Aircraft									
Size										
Airframe unit weight (AUW)	112,672	32,686	30,496	279.145	43,446	96,312	70,253	104,322	96,167	80,723
Empty weight (EW)	177,816	55,560	42,549	320,085	58,107	114,690	97,030	136,900	125,342	91,004
Wetted area	16,650	5,450	4,372	30,800	7,590	13,150	10,770	14,100	12,860	8,426
Technical/performance										
Maximum speed	551	1,147	548	495	326	304	527	491	549	260
Speed class (a)	1	3	1	1	1	1	1	1	--	--
Climb rate	5,120	17,830	5,000	5,160	3,900	3,400	5,900	7,270	6,698	4,650
Useful load fraction	.605	.659	.487	.555	.532	.617	.677	.579	.589	.064
Construction										
Design ultimate load factor	3.00	3.00	4.80	3.75	3.75	3.75	3.75	3.75	3.69	0.56
Carrier capability designator (b)	1	1	1	1	1	1	1	1	--	--
Engine location designator (c)	2	2	2	2	2	2	2	2	--	--
Wing type (d)	2	3	2	2	1	1	2	2	--	--
Ratio of wing area to wetted area	.240	.283	.178	.201	.230	.203	.225	.228	.224	.031
Ratio of (EW-AUW)/AUW	.58	.70	.40	.15	.34	.19	.38	.31	.38	.18
Ratio of avionics weight to AUW	.070	N.A.	.092	.017	.085	.021	N.A.	.023	.043	.031
Number of black boxes	24	26	N.A.	27	17	16	16	26	22	5
Program										
Number of test aircraft	13	30	14	10	9	10	8	5	12	8
Maximum tooling capability	10	8	10	2	18	2	15	9	9	6
New engine designator (b)	2	2	2	2	2	2	1	1	--	--
Contractor experience designator (e)	1	2	1	1	2	1	1	1	--	--
Program type designator (f)	2	1	1	1	2	1	2	1	--	--

N.A. = Not available.
(a)Speed class: 1 = less than Mach .95; 2 = Mach .95 to Mach 1.94; 3 = Mach 1.95 to Mach 2.5.
(b)No = 1; Yes = 2.
(c)Engine location: 1 = embedded in fuselage; 2 = in nacelles under wing.
(d)Wing type: 1 = straight; 2 = swept; 3 = *delta*; 4 = *variable sweep*.
(e)Yes = 1; No = 2.
(f)Program type: concurrent = 1; prototype = 2.

2. With regards to speed, all aircraft in the sample are subsonic with the exception of the B-58 which is a Mach 2 aircraft. Similarly, the B-58 rate of climb is over twice that of the next fastest climbing aircraft in the sample.
3. The sample does not include any aircraft which are both relatively large and relatively fast (such as the B-1A was to have been--airframe unit weight of approximately 150,000 pounds and speed of Mach 2--and the B-1B is to be--dash speed of about Mach 1.2).
4. All of the sample aircraft have engines located in nacelles under the wing and all are land-based. Thus, there is no variation in these two variables and they will not be considered further.
5. The B-58 flight test program utilized more than twice as many aircraft as the next largest program.

There are, of course, differences between the aircraft which are not accounted for in Table 2. Some of the differences relate to the way an aircraft is constructed (materials, manufacturing technology), others to the way the program is managed. In any case, it is difficult to find an aircraft without at least one unique aspect. Therefore, the following list is intended only to be indicative of the types of differences which are difficult to account for in a generalized parametric model.

1. The C-130 and C-133 are prop aircraft while all other sample aircraft utilize turbojet or turbofan engines.
2. The KC-135 was designed and produced more or less concurrently with the commercial 707 model.
3. The B/RB-66 was produced concurrently with the A-3, the aircraft from which it evolved.
4. The B-58's utilization of honeycombed skin panels represented a major state-of-the-art advance.

5. The C-5 program utilized the acquisition concepts of total package procurement and concurrent development and production.

A priori notions regarding the effect an increase in the value of an explanatory variable might have on each of the cost elements are indicated in Table 3.

APPROACH

Potential explanatory variables have been divided into four general categories--size, performance, construction, and program (see Table 3). As discussed in R-3255-AF,[6] the "ideal" airframe cost estimating relationship would incorporate one explanatory variable from each category. Thus, there would be four independent variables per estimating relationship. For the full estimating sample, which has 34 observations, the possible incorporation of four independent variables presents no difficulties since there would still be 29 degrees of freedom left with which to estimate the error term. Unfortunately, the bomber/transport subsample has only eight observations and the incorporation of four explanatory variables would leave only three degrees of freedom with which to estimate the error term. Consequently, the number of explanatory variables considered per equation for the bomber/transport sample was tentatively limited to two.[7]

With respect to the specific combinations of variable categories examined, it is our understanding that all airframe manufacturers use some measure of size (usually weight) as their basic scaling dimension in developing cost estimates (although other factors frequently do enter in). Consequently, it did not seem unreasonable for a similar

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[6]R. W. Hess and H. P. Romanoff, *Aircraft Airframe Cost Estimating Relationships: Study Approach and Conclusions,* The RAND Corporation, R-3255-AF, December 1987, Sec. IV.

[7]We do not mean to suggest that this limit is an "absolute" maximum for it is not (theoretically, one could use six explanatory variables for a bomber/transport equation and still have one degree of freedom left). It simply reflects our *judgment* regarding an appropriate balance between sample size and the potential number of explanatory variables.

Table 3

A PRIORI NOTIONS REGARDING EFFECT OF
EXPLANATORY VARIABLE INCREASE ON COST ELEMENT

Explanatory Variable	Engr.	Tooling	Mfg. Labor	Mfg. Material	Dev. Support	Flight Test	Quality Control	Total Program
Size								
Airframe unit weight (AUW)	+	+	+	+	+	+	+	+
Empty weight (EW)	+	+	+	+	+	+	+	+
Wetted area	+	+	+	+	+	+	+	+
Technical/performance								
Maximum speed	+	+	+	+	+	+	+	+
Speed class (a)	+	+	+	+	+	+	+	+
Climb rate	+	+	+	+	+	+	+	+
Useful load fraction	+	+	+	+				+
Construction								
Design ultimate load factor	+		+	+	+			+
Wing type (b)	+	+	+		+	+		+
Ratio of wing area to wetted area		-	-					-
Ratio of (EW-AUW)/AUW	+		+	+	+	+	+	+
Ratio of avionics weight to AUW	+		+	+	+	+	+	+
Number of black boxes	+		+	+	+	+	+	+
Program								
Number of test aircraft						+		
Maximum tooling capability		+	-					?
New engine designator (c)	+					+		+
Contractor experience designator (d)	+	+	+	+	+	+	+	+
Program type designator (e)	? (f)	? (f)			? (f)	? (f)		? (f)

NOTE: A plus indicates a positive effect; a minus a negative effect. An effect which was thought to be negligible is indicated by a blank, while an uncertain effect is indicated by a question mark.

(a)Speed class: 1 = less than Mach .95; 2 = Mach .95 to Mach 1.94; 3 = Mach 1.95 to Mach 2.5.

(b)Wing type: 1 = straight; 2 = swept; 3 = delta; 4 = variable sweep.

(c)No = 1; Yes = 2.

(d)Yes = 1; No = 2.

(e)Program type: concurrent = 1; prototype = 2.

(f)Not known whether total cost (prototype effort plus full-scale development) for prototype program is greater or less than for concurrent program.

assumption to be made on our part--a size variable must appear in all equations (except for flight test in which case the number of test aircraft is the mandatory variable). Therefore, with this additional restriction, the specific variable combinations that were examined for the bomber/transport sample are as follows:

Size
Size/Performance
Size/Construction
Size/Program

The first step in developing a representative set of CERs was to identify all potentially useful estimating relationships for each cost element resulting from the variable combinations listed above. For this first step, "potentially useful" included only those estimating relationships in which all equation variables were significant at the 5 percent level. Since the number of variable combinations was relatively small, all possible regressions were run and screened for variable significance. Then, each equation satisfying this initial screening criterion was scrutinized in accordance with a set of evaluation criteria dealing with statistical quality and reasonableness of results (these are described in a subsequent subsection).

The final step was the selection of the most suitable estimating relationship for each cost element (i.e., the selection of a representative set). Generally speaking, other things being equal, we tried to select estimating relationships that satisfied the following conditions:

- Each variable is significant at the 5 percent level
- Variables taken collectively are significant at the 5 percent level
- Results are credible
- Unusual residual patterns are absent

If these conditions were satisfied by more than one equation, then the objective was minimization of the standard error of estimate. Traditionally, cost analysts have *tried* to achieve a standard error of estimate of ±20 percent or better. For logarithmic models, this is approximately equivalent to 0.18 (+20 percent, -16 percent). On the other hand, if the conditions were not satisfied by any of the equations, then none was recommended.

Multiple regression analysis was the technique used to examine the relationship between cost and the explanatory variables. Because of time restrictions, only one equation form was investigated--logarithmic-linear. The linear model was rejected because its main analytic property--constant returns to scale--does not correspond to real world expectations. Of the two remaining equation forms considered (logarithmic and exponential), the logarithmic model seemed most appropriate for the cost-estimation process since it minimizes relative errors rather than actual errors as in the exponential model.

Cost element categories which are a function of quantity were examined at a quantity of 100. Developing the estimating relationships at a given quantity rather than utilizing quantity as an independent variable in the regression analysis avoids the problem of unequal representation of aircraft (caused by unequal numbers of lots).

EVALUATION CRITERIA

The estimating relationships obtained in this analysis were evaluated on the basis of their statistical quality, intuitive reasonableness, and predictive properties.

Statistical Quality

Variable Significance. Variable significance was utilized as an initial screening device to reduce the number of estimating relationships requiring closer scrutiny. Normally, only those equations for which all variables were significant at the 5 percent level (one-sided t-test) were reported in this Note. Occasionally, however, this criterion was relaxed in order that a useful comparison could be

provided. When an equation is reported for which not all equation variables are significant at the 5 percent level, it is denoted as follows:

VAR SIG: variable mnemonic

Coefficient of Determination. The coefficient of determination (R^2) was used to indicate the percentage of variation explained by the regression equation.

Standard Error of Estimate. The standard error of estimate (SEE) was used to indicate the degree of variation in the data about the regression equation. It is given in logarithmic form but may be converted into a percentage of the corresponding hour or dollar value by performing the following calculations:

$$\text{(a)} \quad e^{+SEE}-1$$

$$\text{(b)} \quad e^{-SEE}-1$$

For example, a standard error of 0.18 yields standard error percentages of +20 and -16.

F-Statistic. The F-statistic was used to determine collectively whether the explanatory variables being evaluated affect cost. Those equations for which the probability of the null hypothesis pertaining was greater than 0.05 have been identified as follows:

EQ SIG: F-TEST

Equations so identified were not considered for inclusion in the representative equation set.

Multicollinearity. Estimating relationships containing variable combinations with correlations greater than .70 are identified according to the degree of intercorrelation:

MCOL: r(variable mnemonic) > .7, .8, or .9

where the variable identified in parentheses is the equation variable showing the greatest collinearity. Generally speaking, estimating relationships with intercorrelations greater than .8 were avoided when selecting the representative equation set.

Residual Plots. Plots of equation residuals were given cursory examinations for unusual patterns. In particular, plots of residuals versus predictions (log/log) were checked to make sure that the error term was normally distributed with zero mean and constant variance. Additionally, plots of residuals versus time (log/linear) were examined to see whether or not the most recent airframe programs were over- or underestimated. The existence of such patterns resulted in one of the following designations:

RP: DIST (errors not normally distributed)

RP: CUR: OVER or UNDER (most recent aircraft over- or underestimated)

Generally speaking, we *tried* to avoid the use of estimating relationships with patterns in the representative equation set.

Influential Observations. "Cook's Distance" was utilized to identify influential observations in the least squares estimates. For this analysis, an influential observation was defined as one which if deleted from the regression would move the least squares estimate past the edge of the 10 percent confidence region for the equation coefficients. Such observations are identified as follows:

IO: aircraft identification

When an observation was consistently identified as influential, it was reassessed in terms of its relevance to the sample in question. If a reasonable and uniform justification for its exclusion could be developed, then the observation was deleted from the sample and the regressions rerun (in actuality, this occurred only once--when the B-58 was deleted from the bomber/transport sample). Otherwise, the influential observation was simply flagged to alert the potential user to the fact that its deletion from the regression sample would result in a significant change in the equation coefficients.

Reasonableness

The development of airframe cost-estimating relationships requires variable coefficients that provide both credible results and conform whenever possible to the normal estimating procedures employed by the airframe industry. Such credibility and conformity are reflected in both the signs of the variable coefficients as well as their magnitudes.

Exponent Sign. Estimating relationships for which the sign of the variable coefficient was not consistent with a priori notions (see Table 3) are identified in the following manner:

EXP SIGN: variable mnemonic

Estimating relationships containing such inconsistencies were not considered for inclusion in the representative equation set.

Exponent Magnitude. Close attention was also paid to the magnitude of variable coefficients. This applied to exponents which were felt to be too small as well as those which were felt to be too large. Estimating relationships containing such variable coefficients are identified as follows:

EXP G: variable mnemonic

While determinations of this kind are largely subjective, there was one application that was fairly objective. Traditionally, size variables have always provided returns to scale in the production-oriented cost elements (tooling, labor, material, and total program cost). That is, increases in airframe size are accompanied by less than proportionate increases in cost. If the opposite phenomenon is observed, then it is generally believed to be the result of not adequately controlling for differences in construction, materials, complexity, and/or other miscellaneous production factors. Consequently, equations possessing a size-variable coefficient greater than one were always flagged.

When selecting a representative equation set, we generally tried to avoid estimating relationships containing variables with exponents that we felt were either too large or too small (that is, exponents that placed either too much or too little emphasis on the parameter in question). More restrictively, for the production-oriented cost elements, no estimating relationship possessing a size-variable exponent greater than one was considered for a representative equation set.

Predictive Properties

Confidence in the ability of an equation to accurately estimate the acquisition cost of a future aircraft is in large part dependent on how well the acquisition costs of the most recently produced aircraft are estimated. Normally, statistical quality and predictive capability would be viewed as one and the same. Unfortunately, when dealing with airframe costs this is not always the case; our knowledge of what drives airframe costs is limited and the sample is fairly small in size and not evenly distributed with respect to first flight date (see Fig. 1). Consequently, the estimating relationships were also evaluated on the basis of how well costs for a subset of the most recent aircraft in the database are estimated.

An indication of an equation's predictive capability would usually be obtained by excluding a few of the most recent aircraft from the regression and then seeing how well (in terms of the relative deviation) the resultant equation estimates the excluded aircraft. However, in

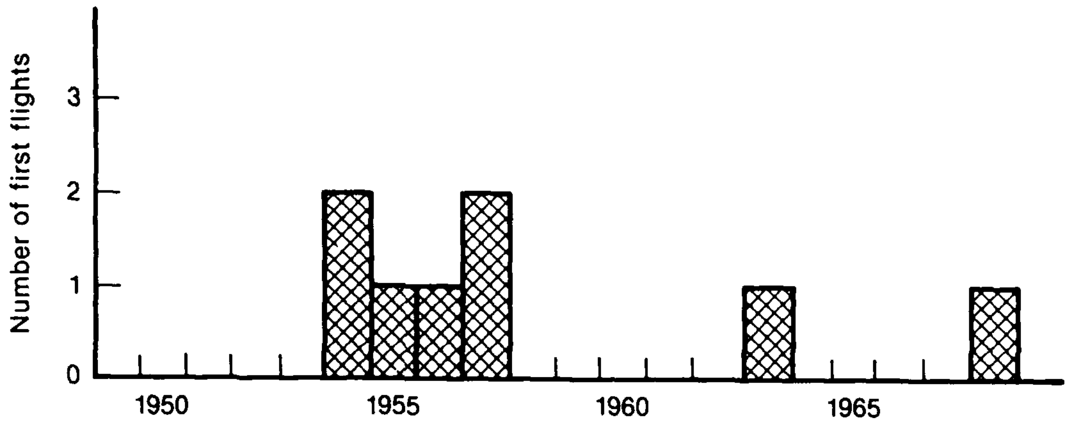

Fig. 1—Number of first flight events as a function of the year of first flight

this case, the small sample size precluded this option. Consequently, the measure of predictive capability used in this analysis was the average of the absolute relative deviations for the B-52, C-5, and C-141. These relative deviations were determined on the basis of the predictive form of the equation and not the logarithmic form used in the regression.[8]

---

[8]If cost is estimated in a log-linear form, such as

$$\ell n \text{ COST} = \beta_0 + \beta_1 \ \ell n \text{ WEIGHT} + \beta_2 \ \ell n \text{ SPEED} + \ell n \ \varepsilon$$

the expected cost is given by

$$\text{COST} = \left(e^{\beta_0} \ \text{WEIGHT}^{\beta_1} \ \text{SPEED}^{\beta_2}\right) \ e^{\hat{\sigma}^2/2}$$

where $\hat{\sigma}^2$ is the actual variance of ε in the log-linear equation. Since the actual variance is not known, the standard error of the estimate may be used as an approximation.

III. INITIAL OBSERVATIONS

This section provides an initial overview of the individual cost element analyses which follow.

INFLUENTIAL OBSERVATIONS

The B-58

Preliminary data analysis consistently identified the B-58 as an influential observation. This is not altogether surprising since it is a relatively small, supersonic aircraft while the remaining bombers and transports are relatively large, subsonic aircraft. Furthermore, an examination of the data plots, especially the engineering, material, development support, and total program cost plots, shows the B-58 to be considerably more expensive on a per pound basis than the other bomber/transport aircraft. Consequently, the B-58 has been excluded from our analysis of the bomber/transport sample.

A comparison of a few of the key variables for the full bomber/transport sample and the sample excluding the B-58 is provided in Table 4. As indicated, by excluding the B-58 from the sample, most of the variation in speed, climb rate, and number of test aircraft is lost.

The B/RB-66 and C-5

The B/RB-66 and C-5, because they are at the extremes of the bomber/transport sample with respect to size, are also consistently identified as influential observations in nearly every equation documented in this Note. This point is easily visualized from the representative data plot provided in Fig. 2. However, we did not feel that size alone was a sufficient reason for excluding the aircraft. Furthermore, note that any attempts to develop simple scaling relationships without the B/RB-66 and C-5 are likely to prove futile since four of the five remaining aircraft (KC-135, B-52, C-133, and C-141) tend to line up vertically with respect to weight (dashed box in Fig. 2).

Table 4

COMPARISON OF FULL BOMBER/TRANSPORT SAMPLE AND SAMPLE EXCLUDING B-58

Variable	Mean		Standard Deviation		Range	
	Full Sample	Excluding B-58	Full Sample	Excluding B-58	Full Sample	Excluding B-58
Airframe unit weight (lb)	96,167	105,235	80,723	82,672	30,496-279,145	30,496-279,145
Empty weight (lb)	125,342	135,311	91,004	93,458	42,549-320,085	42,549-320,085
Wetted area (sq ft)	12,860	13,919	8,426	8,506	4,372- 30,800	4,372- 30,800
Speed (kn)	549	463	260	104	304- 1,147	304- 551
Climb rate (ft/min)	6,698	5,107	4,650	1,271	3,400- 17,830	3,400- 7,270
Useful load fraction	.589	.579	.064	.062	.487- .677	.487- .677
Ratio of wing area to wetted area	.224	.215	.031	.022	.178- .283	.178- .240
AVAUW (a)	.043	.043	.031	.031	.017- .092	.017- .092
EWAUW	.38	.34	.18	.14	.15- .70	.15- .58
Number of test aircraft	12	10	8	3	5- 30	5- 14

(a)No difference in statistics for AVAUW because B-58 value is missing.

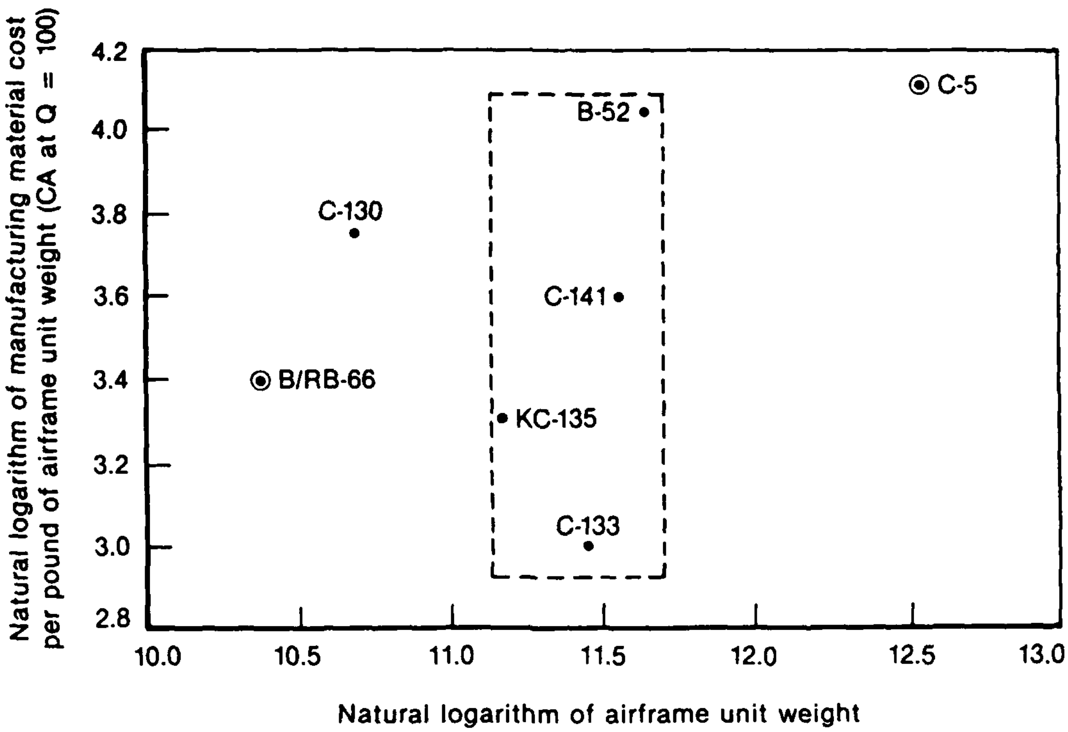

Fig. 2—Effect of B/RB-66 and C-5

PERFORMANCE VARIABLES

Only five equations were determined in which both the size and performance variables were significant at the 5 percent level (two for the engineering cost element, one for tooling, and two for manufacturing material). However, in four of the five cases, the size of the performance variable exponent was counterintuitive, and in the fifth case, the equation as a whole was not significant at the 5 percent level. As stated previously, by excluding the B-58 from the sample, most of the variation in the performance variables was lost.

CONSTRUCTION/PROGRAM VARIABLES

The construction/program variables proved to be of little help in improving the quality of the bomber/transport estimating relationships. There were seven instances where such variables were found to be significant at the 5 percent level but, in each case, the overall equations did not produce results that we viewed as credible.

IV. ENGINEERING

Engineering hours per pound are plotted as a function of airframe unit weight in Fig. 3. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 5. General observations regarding these equations are as follows:

1) The exponents of the size variables in Equations E1, E2, and E3 are all greater than one. An examination of Fig. 2 suggests that this is due in large part to a single aircraft--the C-5 (that is, deletion of the C-5 would result in an equation with a size exponent of less than one).
2) Only one performance variable was found to be significant at the 5 percent level in combination with a size variable--the useful load fraction (USELD). However, in each instance, the sign of its exponent is counterintuitive.
3) The magnitude of the contractor experience designator (EXPDV) in Equations E7 and E8 seems unreasonably large. For example, a contractor without experience would incur engineering costs 75 to 80 percent greater than a contractor with experience.
4) None of the estimating relationships listed in Table 5 is recommended. Although the three size-only equations have fair statistical qualities, their slope is determined largely by a single aircraft--the C-5.

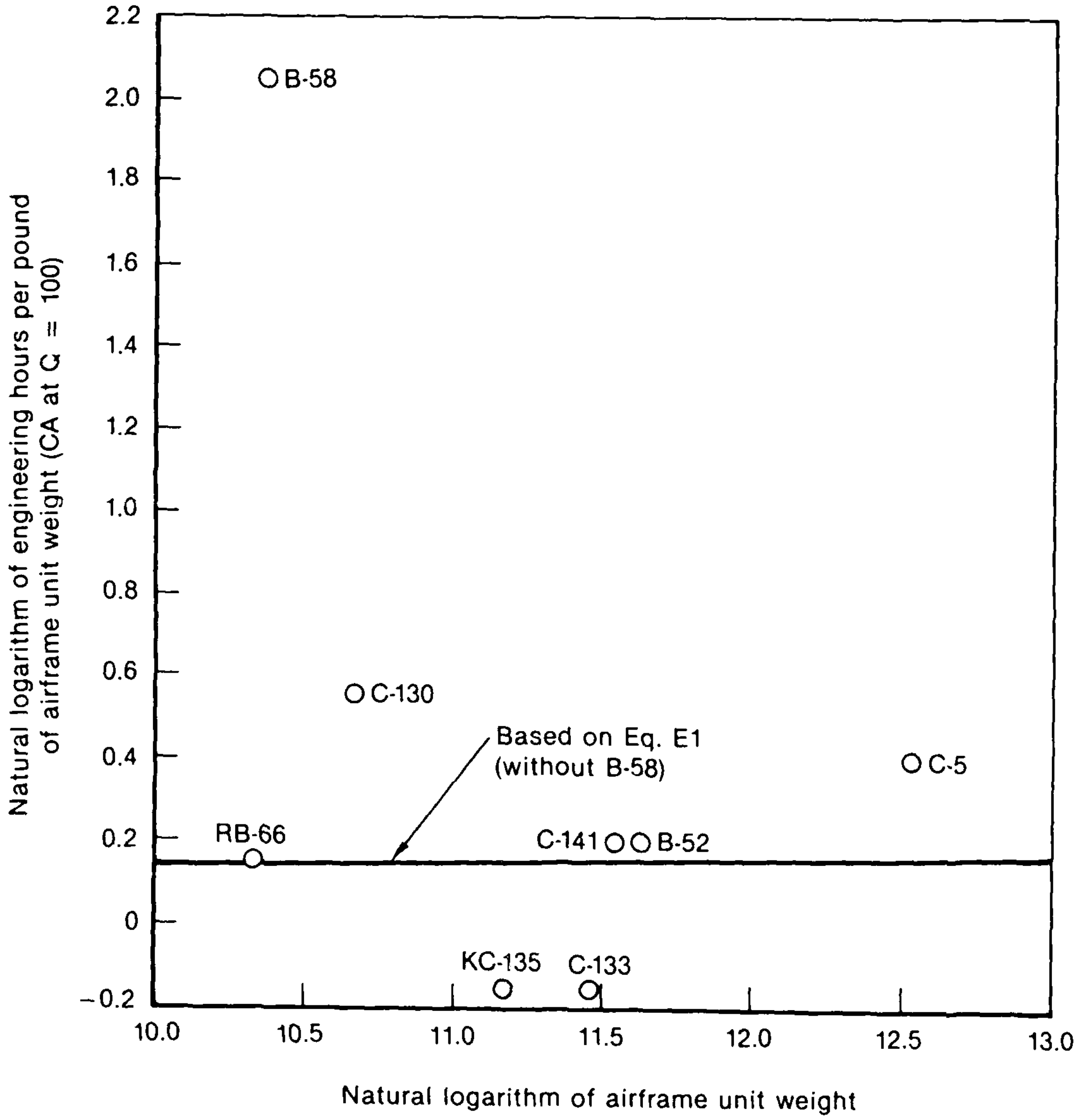

Fig. 3—Engineering hours per pound as a function of airframe unit weight

Table 5

ENGINEERING HOUR ESTIMATING RELATIONSHIPS
(Bomber/transport sample excluding B-58)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) B-52	C-5	C-141	Abs Avg	Comments
	SIZE									
E1	$ENGR_{100} = .105\ AUW^{1.01}$ (.001)(a)	.88	.29	37	7	-4	+16	0	7	IO:C-5,C-130,C-133,KC-135
E2	$ENGR_{100} = .0446\ EW^{1.06}$ (.001)	.86	.31	32	7	-28	+23	-1	17	IO:C-5,C-130,KC-135
E3	$ENGR_{100} = .165\ WTAREA^{1.18}$ (.001)	.87	.30	35	7	-15	+24	+2	14	IO:RB-66,C-5,C-130,C-133, KC-135
	SIZE/PERFORMANCE									
E4	$ENGR_{100} = .0103\ AUW^{1.12}\ USELD^{-1.94}$ (.001) (.052)	.94	.22	34	7	+4	-2	0	2	VAR SIG:USELD EXP SIGN:USELD EXP MAG:USELD IO:RB-66,C-130
E5	$ENGR_{100} = .00242\ EW^{1.21}\ USELD^{-2.22}$ (.001) (.040)	.94	.23	32	7	-20	+5	0	8	EXP SIGN:USELD EXP MAG:USELD IO:RB-66,C-130
E6	$ENGR_{100} = .00538\ WTAREA^{1.38}\ USELD^{-2.64}$ (.000) (.004)	.98	.13	111	7	-4	+1	+3	3	EXP SIGN:USELD EXP MAG:USELD IO:RB-66,C-130,C-133, KC-135
	SIZE/CONSTRUCTION, PROGRAM									
E7	$ENGR_{100} = .0250\ AUW^{1.13}\ EXPDV^{.802}$ (.001) (.053)	.94	.23	33	7	+2	+12	+7	7	VAR SIG:EXPDV EXP MAG:EXPDV LDIFF:EXPDV IO:RB-66,C-5,C-130
E8	$ENGR_{100} = .00758\ EW^{1.21}\ EXPDV^{.870}$ (.001) (.053)	.93	.24	28	7	-23	+19	+7	16	VAR SIG:EXPDV EXP MAG:EXPDV LDIFF:EXPDV IO:RB-66,C-5,C-130

(a)Variable significance is provided in parentheses beneath each variable.

V. TOOLING

Tooling hours per pound are plotted as a function of airframe unit weight in Fig. 4. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 6. General observations regarding these equations are as follows:

1) Of the five equations listed for tooling hours, none, when taken as a whole (F-test), is significant at the 5 percent level.
2) The economies of scale produced by the size variable exponents in Equations T1 through T5 seem somewhat excessive. For example, in Equation T1, a doubling of the airframe unit weight results in only a 32 percent increase in tooling hours. This result is driven largely by the smallest and largest aircraft in the database--the B/RB-66 and the C-5. Furthermore, if these two aircraft were excluded from the sample then no discernible trend would exist (see Fig. 4).
3) None of the size/construction program variable combinations examined satisfied our initial screening criterion with respect to variable significance.
4) None of the estimating relationships listed in Table 6 is recommended.

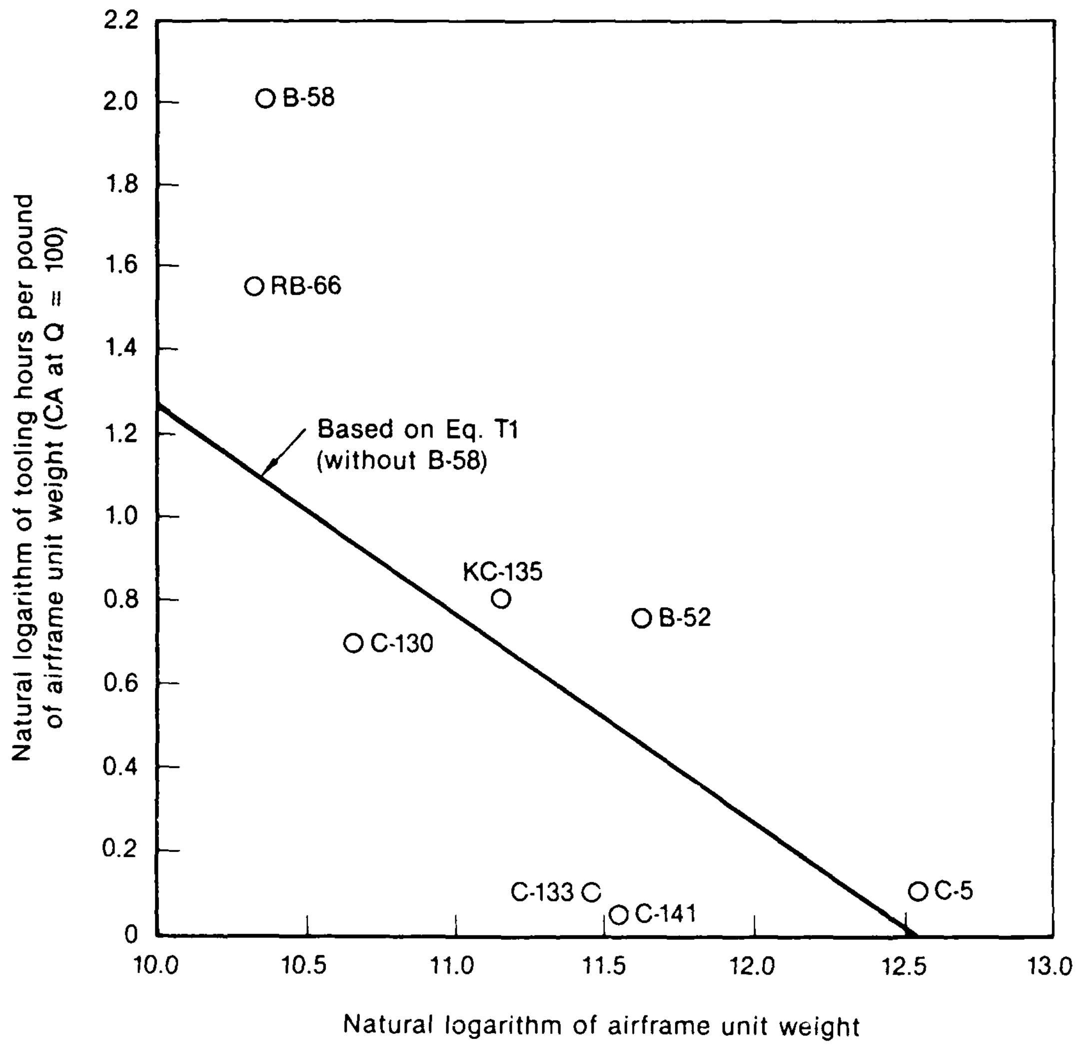

Fig. 4—Tooling hours per pound as a function of airframe unit weight

Table 6

TOOLING HOUR ESTIMATING RELATIONSHIPS
(Bomber/transport sample excluding B-58)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) B-52	C-5	C-141	Abs Avg	Comments
	SIZE									
T1	$TOOL_{100} = 163\ AUW^{.406}$ $(.061)$	.41	.38	3	7	+24	+14	-65	34	VAR SIG:AUW EQ SIG:F-TEST EXP MAG:AUW IO:RB-66,C-5,C-130,C-141
T2	$TOOL_{100} = 76.3\ EW^{.460}$ $(.045)$	.47	.36	4	7	+17	+15	-65	32	EQ SIG:F-TEST EXP MAG:EW IO:RB-66,C-5,C-130, C-141
T3	$TOOL_{100} = 248\ WTAREA^{.446}$ $(.076)$	.36	.40	3	7	+21	+19	-64	35	VAR SIG:WTAREA EQ SIG:F-TEST EXP MAG:WTAREA IO:RB-66,C-5,C-130,C-141
	SIZE/PERFORMANCE									
T4	$TOOL_{100} = .462\ AUW^{.364}\ SP^{1.03}$ $(.046)\ (.047)$	.73	.29	5	7	+10	+13	-73	32	EQ SIG:F-TEST EXP MAG:AUW IO:RB-66,C-5,C-141
T5	$TOOL_{100} = .444\ WTAREA^{.414}\ SP^{1.08}$ $(.052)\ (.045)$	.72	.30	5	7	+6	+16	-72	31	VAR SIG:WTAREA EQ SIG:F-TEST EXP MAG:WTAREA IO:RB-66,C-5,C-141
	SIZE/CONSTRUCTION, PROGRAM									
	None									

VI. MANUFACTURING LABOR

Manufacturing labor hours per pound are plotted as a function of airframe unit weight in Fig. 5. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 7. General observations regarding these equations are as follows:

1) None of the size/performance combinations examined satisfied our initial screening criterion with respect to variable significance.
2) The magnitude of the wing area to wetted area (WGWET) exponents in Equations L4 through L6 seems unreasonably large--a 50 percent increase in the ratio of wing area to wetted area results in 50 to 60 percent fewer manufacturing labor hours.
3) The fit of the three size-only equations (L1, L2, and L3) is determined largely by the B/RB-66. If the B/RB-66 were excluded from the sample, no discernible trend would exist (see Fig. 5).
4) None of the estimating relationships listed in Table 7 is recommended.

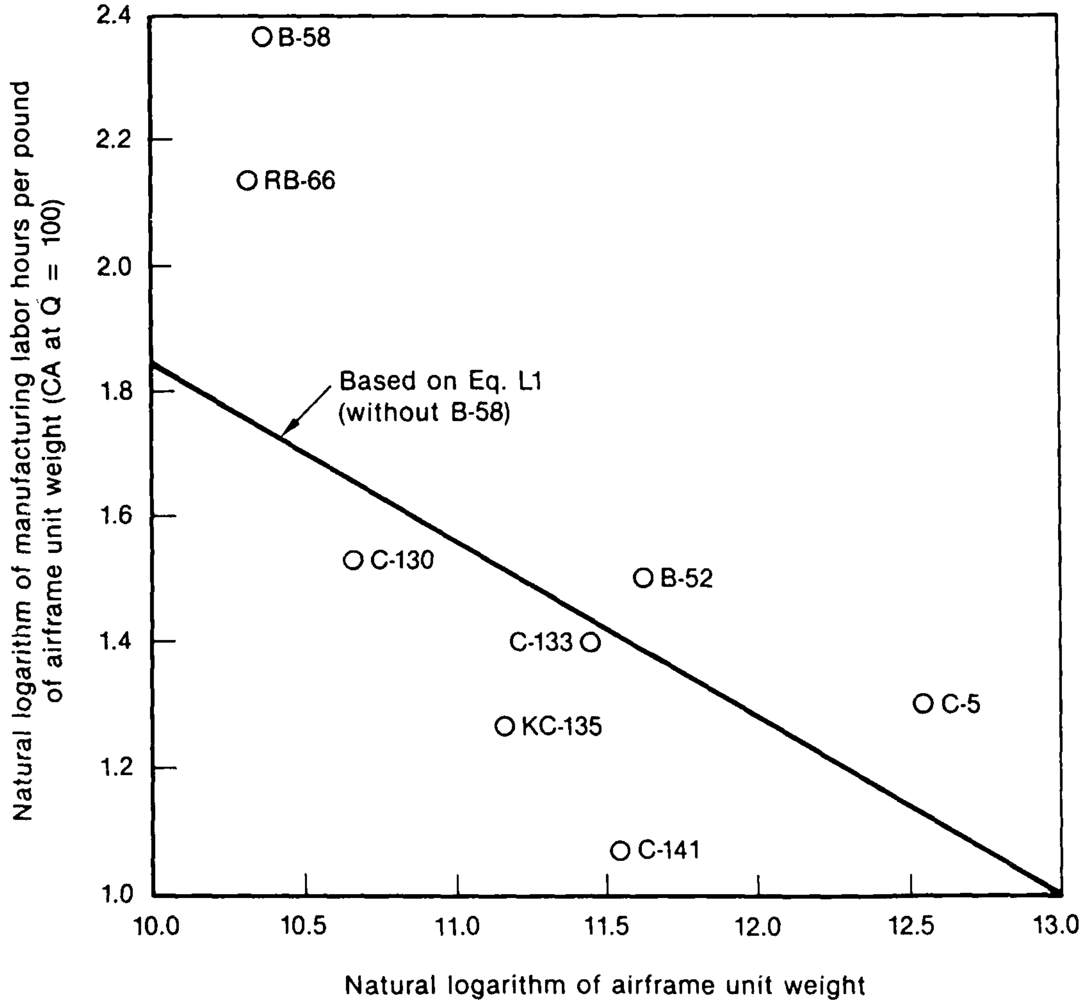

Fig. 5—Manufacturing labor hours per pound as a function of airframe unit weight

Table 7

MANUFACTURING LABOR HOUR ESTIMATING RELATIONSHIPS
(*Bomber/transport sample excluding B-58*)

Eq. No.	Equation	Statistics R^2	Statistics SEE	Statistics F	Statistics N	Relative Deviations (%) B-52	Relative Deviations (%) C-5	Relative Deviations (%) C-141	Relative Deviations (%) Abs Avg	Comments
	<u>SIZE</u>									
L1	$LABR_{100} = 16.1\ AUW^{.683}$ $(.003)$	.80	.27	20	7	+9	+16	-44	23	IO:RB-66,C-5,C-141
L2	$LARR_{100} = 8.81\ EW^{.718}$ $(.004)$	.78	.28	18	7	-4	+21	-44	23	IO:RB-66,C-5,C-141
L3	$LABR_{100} = 31.5\ WTAREA^{.755}$ $(.008)$	.72	.32	13	7	+3	+24	-43	23	IO:RB-66,C-5,C-130
	<u>SIZE/PERFORMANCE</u>									
	None									
	<u>SIZE/CONSTRUCTION, PROGRAM</u>									
L4	$LABR_{100} = .669\ AUW^{.735}\ WGWET^{-1.67}$ $(.002)\ (.064)$	.89	.22	17	7	+25	+2	-29	19	VAR SIG:WGWET EXP MAG:WGWET IO:B-52,RB-66,C-5
L5	$LABR_{100} = .107\ EW^{.813}\ WGWET^{-2.13}$ $(.001)\ (.020)$	.93	.17	28	7	+17	+3	-25	15	EXP MAG:WGWET IO:B-52,RB-66,C-5
L6	$LABR_{100} = .205\ WTAREA^{.894}\ WGWET^{-2.40}$ $(.002)\ (.026)$	.90	.21	18	7	+25	+1	-22	16	EXP MAG:WGWET IO:B-52,RB-66

VII. MANUFACTURING MATERIAL

Manufacturing material cost per pound is plotted as a function of airframe unit weight in Fig. 6. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 8. General observations regarding these equations are as follows:

1) The magnitude of the size variable exponent is greater than one for all equations listed in Table 8.
2) With the exception of the EW/USELD and WTAREA/USELD combinations documented in Equations M4 and M5, none of the size/performance combinations examined satisfied our initial screening criterion relative to variable significance. Furthermore, for the two combinations which did meet our initial criterion, the sign of the performance variable (USELD) exponent is counterintuitive.
3) None of the size/construction, program variable combinations examined satisfied our initial screening criterion with respect to variable significance.
4) None of the estimating relationships listed in Table 8 is recommended.

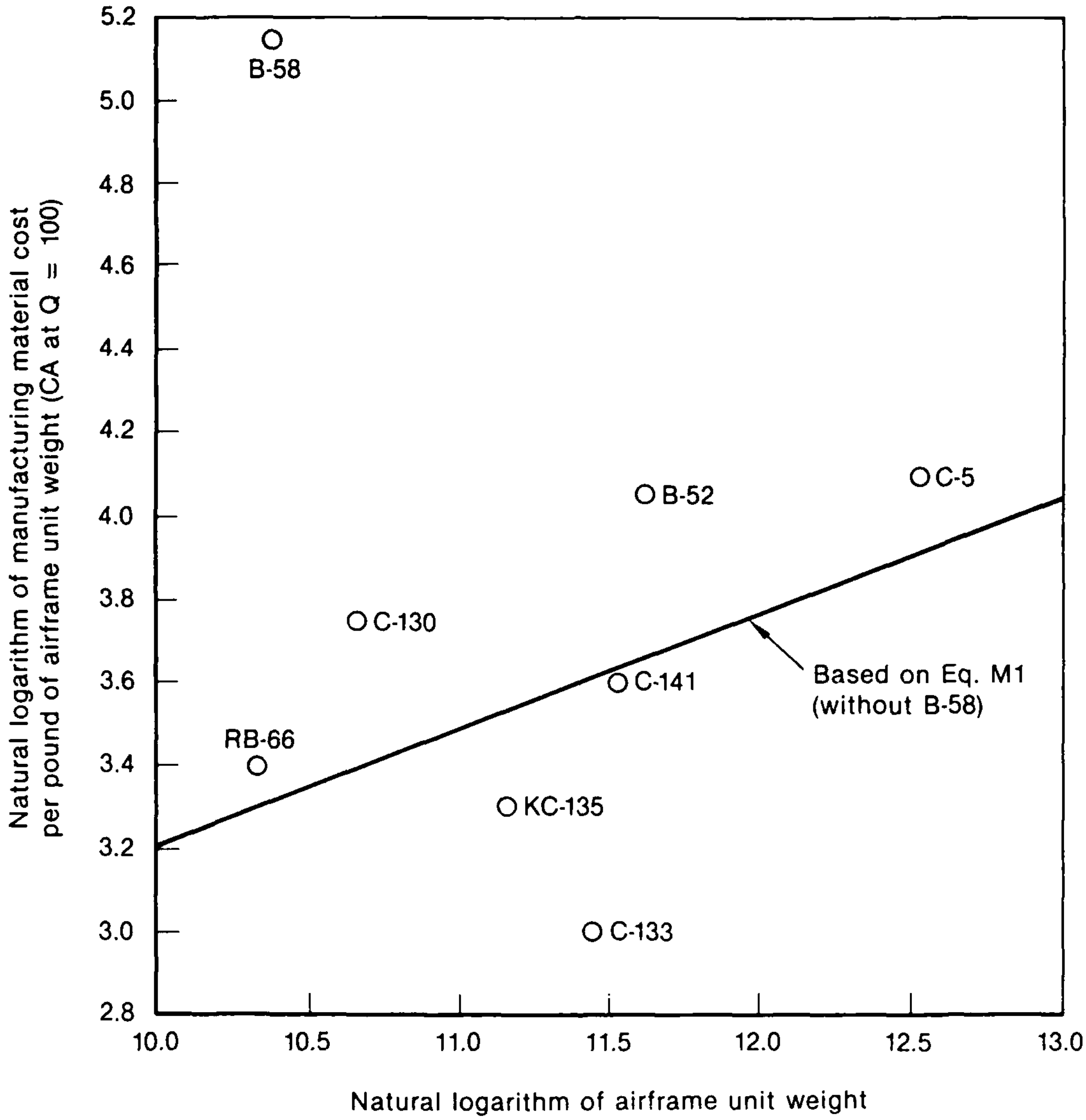

Fig. 6—Manufacturing material cost per pound as a function of airframe unit weight

Table 8

MANUFACTURING MATERIAL COST ESTIMATING RELATIONSHIPS
(Bomber/transport sample excluding B-58)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) B-52	C-5	C-141	Abs Avg	Comments
	SIZE									
M1	$MATL_{100} = .194\ \underset{(.001)}{AUW^{1.26}}$	.87	.39	33	7	+25	+10	-12	16	EXP MAG:AUW IO:B-52,C-5,C-130,C-133
M2	$MATL_{100} = .0417\ \underset{(.001)}{EW^{1.36}}$	.90	.34	44	7	+4	+18	-10	11	EXP MAG:EW IO:C-5,C-130,C-133
M3	$MATL_{100} = .306\ \underset{(.001)}{WTAREA^{1.48}}$	.87	.38	34	7	+16	+20	-9	15	EXP MAG:WTAREA IO:RB-66,C-5,C-133
	SIZE/PERFORMANCE									
M4	$MATL_{100} = .00197\ \underset{(.000)}{EW^{1.52}}\ \underset{(.049)}{USELD^{-2.32}}$	.95	.26	41	7	+10	-2	-10	7	EXP SIGN:USELD EXP MAG:EW EXP MAG:USELD IO:RB-66,C-130,C-133, KC-135
M5	$MATL_{100} = .00870\ \underset{(.001)}{WTAREA^{1.69}}\ \underset{(.039)}{USELD^{-2.75}}$	.95	.28	36	7	+23	-5	-7	12	EXP SIGN:USELD EXP MAG:WTAREA EXP MAG:USELD IO:C-133,KC-135
	SIZE/CONSTRUCTION, PROGRAM									
	None									

VIII. DEVELOPMENT SUPPORT

Development support cost per pound is plotted as a function of airframe unit weight in Fig. 7. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 9. General observations regarding these equations are as follows:

1) None of the size variables in the size-only equations (D1, D2, and D3) is significant at the 5 percent level.
2) None of the size/performance combinations examined satisfied our initial screening criterion relative to variable significance.
3) The sign of the construction variable (BLBOX) in Equation D4 is counterintuitive.
4) None of the estimating relationships listed in Table 9 is recommended.
5) An examination of development support cost as a percentage of nonrecurring engineering cost was also made and is summarized in Table 10.[1] Unfortunately, the percentages span an order of magnitude--from a low of 13 percent to a high of over 130 percent.[2] Consequently, this percentage method of estimating development support cost is not recommended.

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[1]Nonrecurring engineering cost is a logical denominator since the mockups and test articles that make up development support are required for the airframe design effort.

[2]Note that the three aircraft with the lowest development support percentages are all Lockheed aircraft.

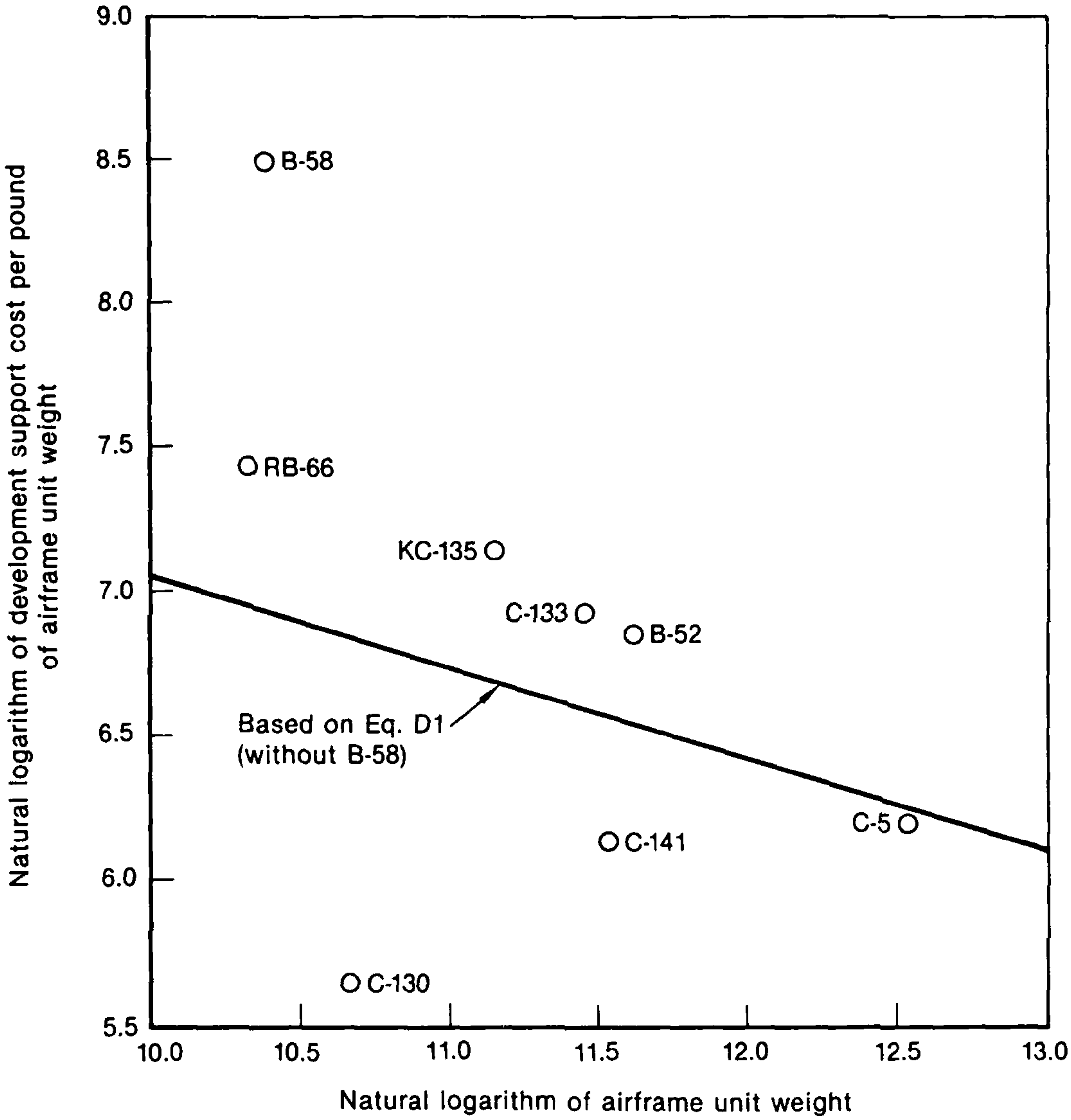

Fig. 7—Development support cost per pound as a function of airframe unit weight

Table 9

DEVELOPMENT SUPPORT COST ESTIMATING RELATIONSHIPS
(Bomber/transport sample excluding B-58)

Eq. No.	Equation	Statistics R^2	SEE	F	N	Relative Deviations (%) B-52	C-5	C-141	Abs Avg	Comments
	SIZE									
D1	$DS = 18.0\ AUW^{.741}$ $(.057)$	.42	.68	4	7	+6	-41	-98	48	VAR SIG:AUW EQ SIG:F-TEST IO:RB-66,C-130
D2	$DS = 6.98\ EW^{.804}$ $(.052)$	.44	.67	4	7	-10	-34	-98	47	VAR SIG:EW EQ SIG:F-TEST IO:RB-66,C-130
D3	$DS = 49.9\ WTAREA^{.790}$ $(.080)$	.35	.72	3	7	-2	-26	-98	42	VAR SIG:WTAREA EQ SIG:F-TEST IO:RB-66,C-130
	SIZE/PERFORMANCE									
	None									
	SIZE/CONSTRUCTION, PROGRAM									
D4	$DS = .00301\ EW^{2.17}\ BLBOX^{-2.84}$ $(.014)\ (.053)$	.86	.43	9	6	+16	-64	+16	32	VAR SIG:BLBOX EXP SIGN:BLBOX EXP MAG:EW EXP MAG:BLBOX MCOL:r > .7 IO:C-5,C-130,C-141

Table 10

DEVELOPMENT SUPPORT COST AS A PERCENTAGE OF UNIT 1 ENGINEERING COST

Aircraft	Unit 1 Engineering Hours	Unit 1 Engineering Cost ($M)(a)	Development Support Cost ($M)	Dev Support as a Percentage of Unit 1 Engr Cost
B-52	5,800,000	159.5	105.5	66
B-58	3,150,000	86.6	165.1	191
B/RB-66	1,600,000	44.0	53.0	120
C-5	23,200,000	651.8	138.5	21
C-130	3,350,000	92.1	12.3	13
C-133	3,000,000	82.5	101.6	123
KC-135	2,500,000	68.8	90.6	132
C-141	6,800,000	187.0	47.5	25

(a)At $27.50 per hour.

IX. FLIGHT TEST

Flight test cost per aircraft is plotted as a function of the quantity of flight test aircraft in Fig. 8. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 11. As indicated, we were not able to identify any estimating relationships which satisfied our initial screening criterion relative to variable significance.

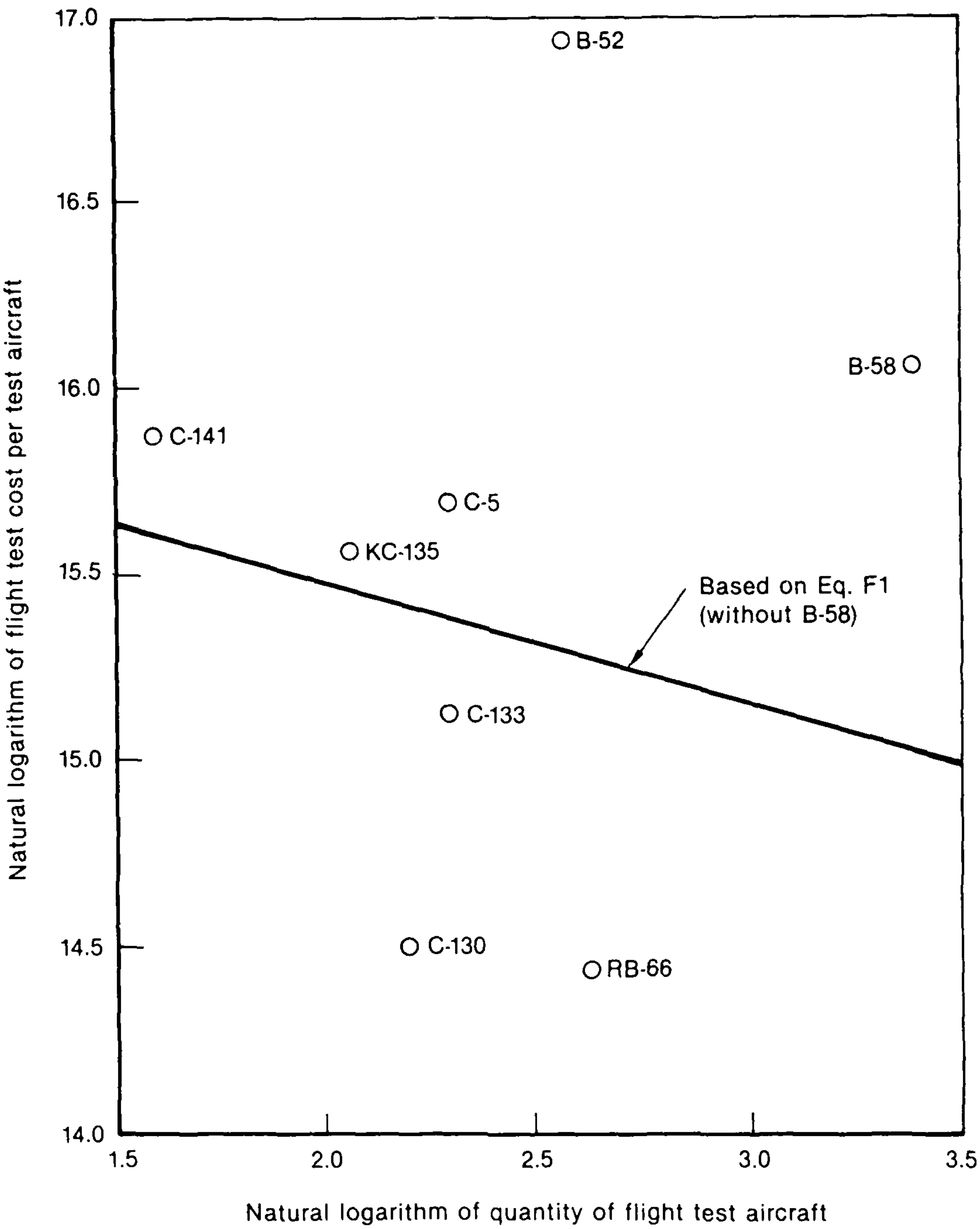

Fig. 8—Flight test cost per test aircraft as a function of the quantity of flight test aircraft

Table 11

FLIGHT TEST COST ESTIMATING RELATIONSHIPS
(Bomber/transport sample excluding B-58)

Eq. No.	Equation	Statistics				Relative Deviations (%)				Comments
		R^2	SEE	F	N	B-52	C-5	C-141	Abs Avg	
	<u>TESTAC</u>									
F1	$FT = 14700\ TESTAC^{.725}$ (.273)	.08	.93	0	7	+68	-22	-17	36	VAR SIG:TESTAC EQ SIG:F-TEST IO:B-52,RB-66,C-141
	<u>SIZE/TESTAC</u>									
	None									
	<u>PERFORMANCE/TESTAC</u>									
	None									
	<u>TESTAC/CONSTRUCTION, PROGRAM</u>									
	None									

X. QUALITY CONTROL

Quality control hours per pound are plotted as a function of airframe unit weight in Fig. 9. The data, which do not fit any obvious patterns, are available for only five aircraft (four excluding the B-58). Consequently, regression analysis does not seem appropriate. However, since quality control is closely related to direct manufacturing labor, it can be estimated as a percentage of same. The ratio of cumulative quality control hours to cumulative manufacturing labor hours is as follows:

Aircraft	Ratio (at Q=100)
B-52	.095
B-58	.163
C-5	.097
C-141	.054
KC-135	.103
Average, all aircraft	.102
Average, excluding B-58	.087

Excluding the B-58, the ratio of cumulative quality control hours to cumulative manufacturing labor hours spans a range of 5.4 percent to 10.3 percent with an average of 8.7 percent.

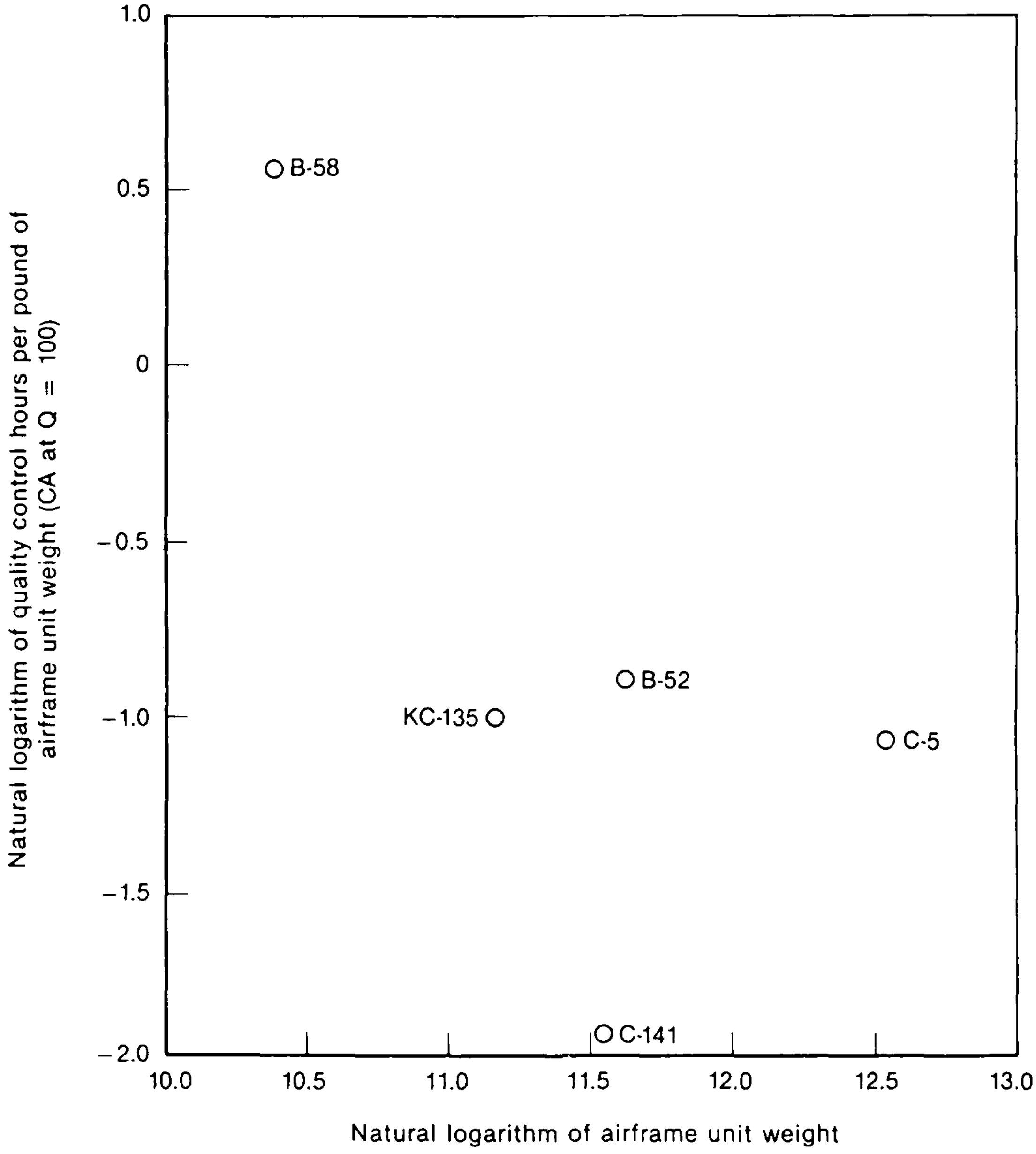

Fig. 9—Quality control hours per pound as a function of airframe unit weight

XI. TOTAL PROGRAM COST

Total program cost per pound is plotted as a function of airframe unit weight in Fig. 10. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 12. General observations regarding these equations are as follows:

- Only one size/performance variable combination (EW/USELD) satisfied our initial screening criterion relative to variable significance. However, the sign of the performance variable exponent is counterintuitive.
- Only one size/construction, program variable combination satisfied our initial screening criterion relative to variable significance. However, the magnitude of the construction variable (AVAUW) exponent seems too large--each doubling of the avionics weight to airframe unit weight ratio results in a 32 percent increase in total program cost. Such a result may be reasonable for fighters but does not seem so for large, subsonic aircraft.
- The fit of the three size-only equations (P1, P2, and P3) is determined largely by the B/RB-66. If the B/RB-66 were excluded from the sample, no discernible trend would exist (see Fig. 10).
- None of the estimating relationships listed in Table 12 is recommended.

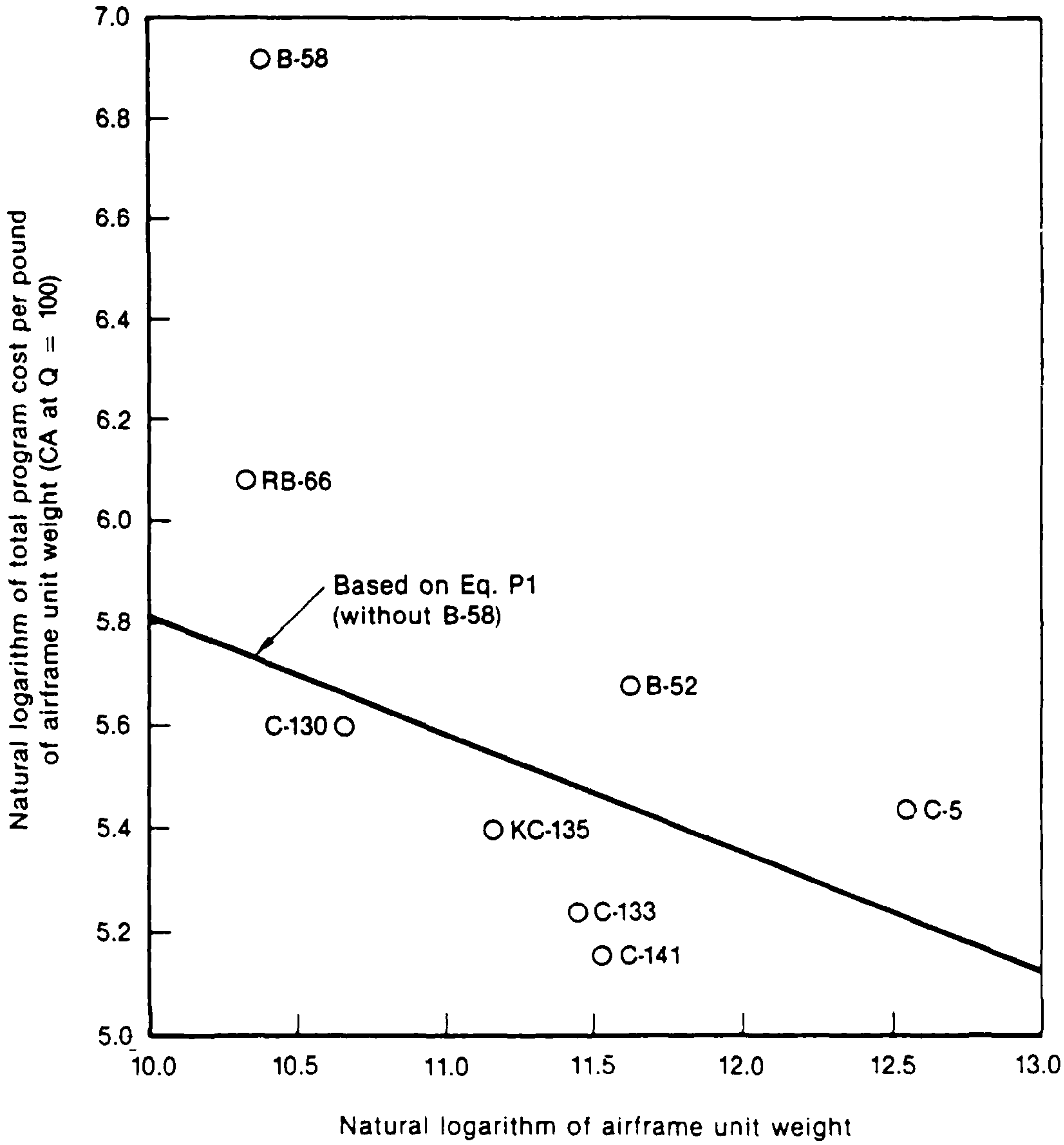

Fig. 10—Total program cost per pound as a function of airframe unit weight

Table 12

TOTAL PROGRAM COST ESTIMATING RELATIONSHIPS
(Bomber/transport sample excluding B-58)

Eq. No.	Equation	Statistics				Relative Deviations (%)				Comments
		R^2	SEE	F	N	B-52	C-5	C-141	Abs Avg	
	SIZE									
P1	$PROG_{100} = 385\ AUW^{.761}$ (.002)	.83	.27	24	7	+18	+16	-38	24	IO:RB-66,C-5,C-141
P2	$PROG_{100} = 163\ EW^{.817}$ (.002)	.85	.25	28	7	+5	+21	-38	21	IO:RB-66,C-5,C-141
P3	$PROG_{100} = 699\ WTAREA^{.857}$ (.004)	.77	.31	17	7	+12	+23	-36	24	IO:RB-66,C-5
	SIZE/PERFORMANCE									
P4	$PROG_{100} = 17.4\ EW^{.927}\ USELD^{-1.70}$ (.001) (.054)	.93	.20	25	7	+9	+6	-38	18	VAR SIG:USELD EXP SIGN:USELD EXP MAG:USELD IO:RB-66,C-5,KC-135
	SIZE/CONSTRUCTION, PROGRAM									
P5	$PROG_{100} = 112\ AUW^{.991}\ AVAUW^{.406}$ (.004) (.051)	.94	.20	24	6	-16	+17	-22	18	VAR SIG:AVAUW IO:B-52,RB-66,C-5 EXP MAG:AVAUW

XII. CONCLUSIONS

We were not able to identify any acceptable estimating relationships for any of the individual cost elements or for total program cost. We suggest that users develop estimates for proposed bomber/transport aircraft either on the basis of analogy (using the data provided in this volume) or by using the equation set developed for all mission types.

We believe that our inability to develop a set of statistically derived cost-estimating relationships for bomber/transport aircraft is the result of a sample that is both small and not as homogeneous as it appears at first glance. For example:

- The B-58 is a Mach 2 aircraft while all other aircraft in the sample are subsonic;
- The C-130 and C-133 are propeller-driven aircraft;
- The B/RB-66 and KC-135 were evolutionary developments;
- The B-52 was into its fourth series (the "D" version) by the time 100 aircraft had been produced;
- The C-141 had a very large percent of subcontract effort (approximately 50 percent), which may have distorted the distribution of equivalent in-plant cost (Ref. 2, p. 50);
- The C-5 program utilized the acquisition concepts of total package procurement and concurrent development and production.

Given this amount of diversity in so small a sample, it would have been surprising if we had been able to develop a credible set of CERs.

COST-QUANTITY SLOPES

Minimum, maximum, and average cost-quantity slopes for the bomber/transport subsample (excluding the B-58) are provided in Table 13

Table 13

CUMULATIVE TOTAL COST QUANTITY SLOPES

	Engineering	Tooling	Mfg Labor	Mfg Material	Quality Control	Total Program
Number of observations	7	7	7	7	4	7
Range (%)	110-116	108-122	146-168	160-182	146-158	130-138
Average (%)	114	114	154	168	152	136
Exponent	.189	.189	.623	.748	.604	.444

NOTES: Results are based on first 200 units; sample excludes B-58; cumulative average slope = cumulative total slope divided by two.

FULLY BURDENED LABOR RATES

All cost elements estimated directly in dollars are in 1977 dollars. Suggested 1977 fully burdened hourly labor rates (and those used to estimate total program cost) are:

Engineering	27.50
Tooling	25.50
Manufacturing labor	23.50
Quality Control	24.00

For estimates in 1986 dollars, the following hourly labor rates and adjustment factors are suggested:

Engineering	59.10
Tooling	60.70
Manufacturing labor	50.10
Quality control	55.40
Manufacturing material (index)	1.94
Development support (index)	1.94
Flight test (index)	1.94
Total program (index)	2.13

The 1986 labor rates are based on data provided by seven contractors:

Labor Category	Hourly Rates ($) Average	Range	Range About Average (%)
Engineering	59.10	47.70-70.00	-19, +18
Tooling	60.70	56.50-65.00	7, +7
Manufacturing labor	50.10	41.70-58.00	-17, +16
Quality control	55.40	49.10-62.60	-11, +13

Note that with the exception of tooling, the range about the average rate is at least ±10 percent. Such differences could arise from differences in accounting practices, business bases, and capital investment. Irrespective of cause, however, labor rate variation is one more component of a larger uncertainty which already includes the error associated with statistically derived estimating relationships and questions about the proper cost-quantity slope. Furthermore, in addition to the inter-contractor differences, these rates are also subject to temporal change--accounting procedures, relative capital/labor ratio, etc. Thus, the 1986 fully burdened rate is qualitatively different from the 1977 rate. Unfortunately, trying to estimate the magnitude of such quality changes, even very crudely, is a study in itself and beyond the scope of this analysis.

The material, development support, and flight test escalation indexes are based on data provided in AFR 173-13.[1] For the years 1977-1984, the airframe index presented in Table 5-3 ("Historical Aircraft Component Inflation Indices") was used. For the years 1985 and 1986, the aircraft and missile procurement index presented in Table 5-2 ("USAF Weighted Inflation Indices Based on OSD Raw Inflation and Outlay Rates") was used. The total program cost adjustment factor was then determined on the basis of a weighted average (at Q = 100) of the individual cost elements.

[1]See Ref. 6.

Appendix

CORRELATION MATRIXES

This appendix contains correlation matrixes for the full bomber/transport estimating sample. Table A.1 provides Pearson correlation coefficients for all possible pairwise combinations of dependent and independent variables. Table A.2 provides coefficients for all possible pairwise combinations of independent variables.

Table A.1

CORRELATION MATRIX: COST VARIABLES WITH
POTENTIAL EXPLANATORY VARIABLES

EXPLANATORY VARIABLES	COST VARIABLES						
	ln ENGR	ln TOOL	ln LABR	ln MATL	ln DS	ln FT	ln PROG
SIZE							
ln AUW	0.58	0.37	0.80	0.71	0.35	0.11	0.66
ln EW	0.63	0.46	0.83	0.77	0.42	0.26	0.72
ln WTAREA	0.58	0.35	0.77	0.72	0.31	0.14	0.64
PERFORMANCE							
ln SP	0.39	0.64	0.11	0.33	0.55	0.72	0.41
ln SPCLS	0.42	0.36	- 0.02	0.23	0.41	0.61	0.28
ln CLIMB	0.45	0.43	0.00	0.32	0.43	0.62	0.32
ln USELD	0.28	0.24	0.06	0.25	0.56	0.55	0.23
CONSTRUCTION							
ln ULTLD	- 0.61	- 0.43	- 0.29	- 0.61	- 0.40	- 0.84	- 0.51
ln WGTYPE	0.39	0.70	0.25	0.40	0.60	0.65	0.48
ln WGWET	0.45	0.20	- 0.09	0.37	0.16	0.66	0.22
ln EWAUW	- 0.16	0.13	- 0.44	- 0.17	0.03	0.55	- 0.18
ln AVAUW	- 0.65	0.05	- 0.41	- 0.49	- 0.17	0.20	- 0.37
ln BLBOX	0.86	0.63	0.58	0.87	0.40	0.59	0.75
PROGRAM							
ln TESTAC	0.22	0.52	0.12	0.12	0.44	0.62	0.30
ln TOOLCP	- 0.49	- 0.32	- 0.76	- 0.45	- 0.55	- 0.07	- 0.59
ln ENGDV	0.18	0.27	0.32	0.14	0.06	0.21	0.28
ln EXPDV	0.17	- 0.13	- 0.36	- 0.14	- 0.34	0.11	- 0.13
ln PRGDV	- 0.28	- 0.12	- 0.32	- 0.14	- 0.38	0.03	- 0.28

Table A.2

CORRELATION MATRIX FOR IDENTIFICATION OF PAIRWISE COLLINEARITY

	SIZE			TECHNICAL/PERFORMANCE				CONSTRUCTION						PROGRAM				
	ln AUW	ln EW	ln WTAREA	ln SP	ln SPCLS	ln CLIMB	ln USELD	ln ULTLD	ln WGTYPE	ln WGWET	ln EWAUW	ln AVAUW	ln BLBOX	ln TESTAC	ln TOOLCP	ln ENGDV	ln EXPDV	ln PRGDV
SIZE																		
ln AUW	1.00																	
ln EW	0.99	1.00																
ln WTAREA	0.99	0.99	1.00															
TECHNICAL/PERFORMANCE																		
ln SP	-0.31	-0.19	-0.32	1.00														
ln SPCLS	-0.45	-0.37	-0.44	0.82	1.00													
ln CLIMB	-0.32	-0.22	-0.32	0.93	0.89	1.00												
ln USELD	0.11	0.18	0.17	0.34	0.43	0.44	1.00											
CONSTRUCTION																		
ln ULTLD	-0.17	-0.29	-0.25	-0.43	-0.54	-0.49	-0.69	1.00										
ln WGTYPE	-0.07	0.04	-0.10	0.93	0.56	0.82	0.27	-0.29	1.00									
ln WGWET	-0.19	-0.07	-0.10	0.56	0.71	0.71	0.66	-0.88	0.37	1.00								
ln EWAUW	-0.67	-0.54	-0.62	0.67	0.56	0.60	0.26	-0.44	0.51	0.63	1.00							
ln AVAUW	-0.67	-0.58	-0.67	0.47		0.04	-0.46	0.16	0.29	-0.14	0.85	1.00						
ln BLBOX	0.32	0.42	0.30	0.62	0.37	0.58	-0.16	-0.46	0.72	0.32	0.16	-0.03	1.00					
PROGRAM																		
ln TESTAC	-0.47	-0.39	-0.48	0.69	0.79	0.56	0.15	-0.38	0.44	0.38	0.55	0.63	0.25	1.00				
ln TOOLCP	-0.62	-0.57	-0.56	0.19	0.05	0.19	-0.03	-0.02	0.14	0.33	0.71	0.64	-0.19	-0.04	1.00			
ln ENGDV	-0.11	-0.11	-0.13	0.00	0.22	-0.14	-0.37	-0.10	-0.20	-0.10	-0.01	0.30	0.10	0.65	-0.34	1.00		
ln EXPDV	-0.57	-0.54	-0.51	0.29	0.65	0.43	0.06	-0.36	-0.03	0.63	0.43	0.00	-0.02	0.49	0.37	0.33	1.00	
ln PRGDV	-0.07	-0.03	0.03	-0.22	-0.29	-0.28	0.20	-0.27	-0.24	0.26	0.34	0.39	-0.47	-0.17	0.64	-0.15	0.15	1.00

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